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A review of the economical and optimum thermal insulation thickness for building applications

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ABSTRACT

Energy conservation is an increasingly important issue for the residential sector. Therefore, attention towards the thermal performance of building materials, particularly thermal insulation systems for buildings, has grown in recent years. In this study, a literature review on determining the optimum thickness of the thermal insulation material in a building envelope and its effect on energy consumption was carried out. The results, the optimization procedures and the economic analysis methods used in the studies were presented comparatively. Additionally, a practical application on optimizing the insulation thickness was performed, and the effective parameters on the optimum value were investigated.

Contents

1. Introduction

In many countries, building energy consumption accounts for approximately 40% of global energy demands, and the energy requirement for space heating and cooling of a building is approximately 60% of the total energy consumed in buildings, which accounts for the largest percentage of energy usage [1–9]. The proper design and selection of a building envelope and its components are an efficient means to reduce the space heating–cooling loads. As such, thermal insulation is one of the most valuable tools in achieving energy conservation in buildings [10–13]. Therefore, determining both the type of thermal insulation material and the economic thickness of the material used in the building envelope are the main subjects of many engineering investigations. These studies help to reduce building energy use (annual energy requirements for heating and cooling), the size of air-conditioning and heating systems in buildings and to achieve a desirable indoor thermal comfort for occupants.

The concept of economic thermal insulation thickness considers the initial cost of the insulation system plus the ongoing value of energy savings over the expected service lifetime of the insulation. The optimum economic thickness is the value that provides the minimum total life-cycle cost, as illustrated in Fig. 1. The thickness is a function of the following: the building type, function, shape, orientation, construction materials, climatic conditions, insulation material and cost, energy type and cost, and the type and efficiency of air-conditioning system [13–16]. As the insulation thickness in a wall increases, the heating and cooling transmission loads for

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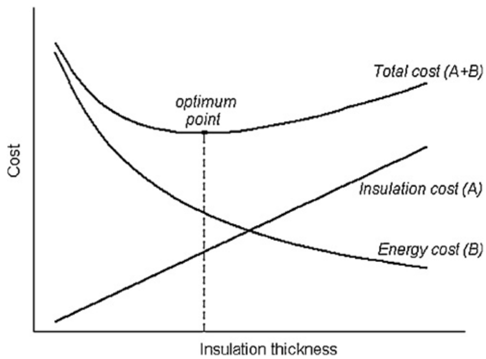

Fig. 1. Optimum insulation thickness.

a building decrease. The transmission loads are used as the input data for an economic model to determine the variation in the cost of the insulation plus the present value of energy consumption, considered lost energy, over the lifetime of the building with such insulation.

In most studies, the optimum insulation thickness computations were performed based mainly on the heating and cooling loads and other parameters such as the costs of the insulation material and energy, efficiencies of the heating and cooling systems, the lifetime, and the current inflation and discount rates. For that reason, the annual heating and cooling energy requirements of a building were the main inputs required to analyze the optimum insulation thickness. Most studies estimated the heating and cooling energy requirements by the degree-time concept (degree-day, *DD*, or degree-hour, *DH*), which is one of the simplest methods that is applied under static conditions [9,16–23]. On the other hand, only a limited number of analytical techniques were applied to analyze the transient behavior of multilayer building envelopes [24–26].

In this paper, the studies related to the effects of thermal insulation used in building walls on reducing greenhouse gas emission were presented first. The variation of carbon dioxide (CO_2) and sulfur dioxide (SO_2) emissions in various geographical regions with different fuel types used and insulation materials were investigated. Then, the studies related to determining the optimum insulation thickness for different wall configurations were presented. The studies on the properties of thermal insulation materials and their applications in building envelopes were investigated. After examining the financial analysis methods used to obtain an economic insulation thickness, a simple and practical application on determine the optimum insulation thickness for external walls was conducted.

2. The effects of thermal insulation in the building envelope on reducing emissions and environmental impacts

A proper amount of thermal insulation in the building envelope helps to reduce the cooling and heating energy demands of a building and its associated CO_2 and SO_2 emissions into the atmosphere. Some researchers [27–29] have focused on reducing CO_2, SO_2 and other greenhouse gas emissions by applying an optimum thermal insulation thickness to the external walls of buildings. Mahlia and Iqbal [29] concentrated on the potential cost savings and emission reductions in the Maldives by installing different insulation materials with optimum thicknesses and air gaps in the building walls. They concluded that, without an air gap in the wall, the fiberglass–urethane material had the greatest life-cycle savings and was the most economical insulation material, whereas the rigid fiberglass material was the least economical. Moreover, when an air gap was introduced in the composite wall, urethane was the least economical. They specified that the emissions could be reduced by more than 77% when fiberglass–urethane was installed with an optimum thickness and an air gap of 0.06 m.

Several investigators carried out studies on different *DD* regions in Turkey classified as the TS 825 standard-Thermal Insulation in Buildings. The standard TS 825 defined the rules of calculating the heating energy demand in buildings and gave the reference and permeable values for heating energy [30]. According to TS 825, Turkey is divided into four climate regions based on *DD* values, in which the fourth region has the most severe winter conditions and requires a larger amount of energy to heat buildings. According to the standard, the thermal transmittance values (U) for walls, floors, windows, glazing and ground floor for each region are given in Table 1. Maximum heating loads in terms of area and volume (A/V) for each region are also presented in Table 1, where A is the area of the building envelope and V is the heated volume of the building [31,32].

Dombayci et al. [33] determined the optimum insulation thickness od expanded polystyrene and rock wool for Denizli, located in the second climate region in Turkey. Dombayci [27] investigated the environmental impact of the thermal insulation applied to the external walls because of minimizing the energy usage and reducing emission for Denizli. In the theoretical calculations, coal was used as the fuel source and expanded polystyrene was used as the insulation material. He determined that CO_2 and SO_2 emissions were cut by 42% (approx. 370,000 tons/year) when the optimum insulation thickness was used in the external walls of buildings. In another study, one of the coldest provinces of Turkey, Erzurum, was investigated by Comakli and Yuksel [28]. When fuel-oil was used for heating, they determined that CO_2 emissions were cut by 27% with an optimized insulation thickness in the external building walls. Moreover, this study emphasized that this ratio could be increased up to 50% (approx. 450,000 tons/year) by employing more energy saving techniques in the other parts of buildings. Yildiz et al. [34] focused on two cities, Izmir and Ankara, which are located in the first and third *DD* regions, respectively. In that study, they obtained the variation of optimum insulation thickness with different fuel types and two common insulation materials (glass wool and rock wool).

In one of the more recent studies, Ozkan and Onan [35] investigated the effects of altering the glazing area percentage of windows, which ranged from 10 to 50%, on the heating energy requirements and the optimum insulation thickness with the P_1–P_2 method for four *DD* regions in Turkey. The results showed that optimum insulation thicknesses varied between 0.036 and 0.087 m for extruded polystyrene foam (XPS) and natural gas. Moreover, CO_2 emissions decreased by 50.91% for natural gas when the optimum insulation thickness was used. On the other hand, the CO_2 and SO_2 emissions decreased by 54.67% with the use of fuel-oil and the optimum insulation thickness. Above mentioned studies and their results are summarized in Table 2, which shows the insulation materials, fuels and economic models used along with the main findings of the studies.

3. Optimization of thermal insulation thickness for the building envelope and its effect on energy consumption

Thermal insulation is known to play a critical role in saving energy by reducing the rate of heat transfer and determining the amount of insulation material required in walls is a key factor. Numerous studies estimated the optimum thickness of thermal insulation used in external walls for different climate conditions [4,15,26,36–43]. Most studies dealing with optimum insulation thickness were based on either heating loads [9,19,20,22,38,41] or cooling loads [42–46], while some works considered both annual heating and cooling loads [16–18,23].

Table 1
U values for building envelope and heating energy requirement in TS 825 standard.

Regions defined in TS-825	Overall heat transfer coefficients, U (W/m^{2}K)				Annual heating energy req. (for $A/V < 0.2$)	
	Walls	Ground floor	Floor	Windows	(kWh/m^2)	(kWh/m^3)
1. Region	0.70	0.45	0.70	2.40	19.2	6.2
2. Region	0.60	0.40	0.60	2.40	38.4	12.3
3. Region	0.50	0.30	0.45	2.40	51.7	16.6
4. Region	0.40	0.25	0.40	2.40	67.3	21.6

3.1. Studies using the degree-time concept

As mentioned previously, reliably determining the heating and cooling transmission loads of buildings is an important issue in optimizing the insulation thickness. To estimate the amount of energy required for heating or cooling, one of the commonly used methods is the degree-days or degree-hours method. This is calculated as the difference between the base temperature and the mean outdoor air temperature and the method was used by many authors [9,10,17–22,47,48]. Using this method requires little data and provides adequate results for simple systems and applications [49]. The total number of annual heating and cooling degree-days (*HDD*s and *CDD*s) is calculated by

$$HDD = \sum_{\text{days}} (T_b - T_o)^+ \tag{1}$$

$$CDD = \sum_{\text{days}} (T_o - T_b)^+ \tag{2}$$

where T_b is the base temperature and T_o is the daily mean outdoor air temperature. The plus sign above the parentheses indicates that only positive values are to be counted. The heating and cooling degree-hours can be calculated in a similar manner with the hourly instead of the daily data.

Kaynakli [38] investigated the residential heating energy requirements and optimum insulation thickness for a prototype building in a sample city in Turkey, Bursa. The variation in the annual heating energy requirement of the building for various architectural design properties (such as air inflation rate, glazing type, and glazing area) and the optimum insulation thicknesses with different fuel types were investigated. By using the *DH*s depending on outdoor air temperature data for 14 years (from 1992 to 2005), the heating energy requirement was calculated. Consequently, the optimum insulation thickness for Bursa was found to vary between 0.053 and 0.124 m depending on the type of fuel used for heating. Bolatturk [17] investigated the optimum insulation thicknesses and payback periods for seven cities located in the warmest zone in Turkey based on heating and cooling degree-hours (*HDH*s and *CDH*s). He emphasized that optimizing the insulation thickness with respect to the cooling load was more appropriate for warm than cold regions because the thicknesses of the insulation material (polystyrene) varied between 0.032 and 0.038 m for cooling degree-hours and between 0.016 and 0.027 m for heating degree-hours. A similar study was carried out by Ozel and Pihtili [18] who used *HDD*s and *CDD*s to estimate the consumed energy. The effect of insulation thickness on the glazing area was investigated numerically in another study by the same authors, Ozel and Pihtili [50]. Ucar and Balo [40] determined the optimum insulation thicknesses numerically, depending on the principal fuel types used for heating, for four cities (Kocaeli, Aydin, Elazig and Agri) that are located in different *DD* regions in Turkey. In that work, typical insulation materials such as the Foamboard 3500, Foamboard 1500, extruded polystyrene and fiberglass were studied using the P_1–P_2 method for amount of net energy savings. A more recent and similar study was carried out by Ucar and Balo [23] to optimize the insulation thickness for only certain cities (Mersin, Sanliurfa, Elazig and Bitlis) in Turkey on the basis of *HDD*s and *CDD*s. In that study, four different insulation materials (extruded polystyrene, expanded polystyrene, nil siding and rock wool) were considered. The amount of the net energy cost savings were calculated using the P_1–P_2 method. The optimum insulation thicknesses were calculated based on heating fuel types in Bolatturk [9] and Aytac and Aksoy [51] for only one or several cities in Turkey. In general, these

Table 2
The summary results of the studies related to environmental impacts of thermal insulation.

Paper	Economic Method	Place	Opt. insulation thickness	Insulation material	Reduction in emissions	Fuel
Mahlia and Iqbal [29]	*LCC*	Maldives	0.015–0.06 m (depending on insulation material and air gap thickness)	Fiberglass–urethane, fiberglass (rigid), urethane (rigid), perlite, extruded polystyrene, urethane (roof deck)	65–77%	Diesel
Dombayci [27]	–	Denizli/Turkey	0.095 m (calculated in Dombayci et al. [33])	Expanded polystyrene	Approx. 370,000 tons/year (42%) for CO_2, SO_2	Coal
Comakli and Yuksel [28]	–	Erzurum/Turkey	0.10 m (calculated in Comakli and Yuksel [41])	Styrofoam	27% for CO_2 and other gases emissions	Fuel-oil
Yildiz et al. [34]	*LCC*	Turkey (Izmir and Ankara)	0.05–0.12 m depending on fuel type (for glass wool)	Glass wool, rock wool	Approx. 35% in Ankara (for coal)	Coal, natural gas, fuel oil, LPG, electricity
Ozkan and Onan [35]	P_1–P_2	For four *DD* regions in Turkey	0.0364–0.087 m depending on *DD* regions (for XPS)	Extruded polystyrene foam, rock wool	51% for CO_2 (natural gas), 55% for CO_2, SO_2 (fuel-oil)	Natural gas, fuel oil

Table 3
The summary results of the studies related to optimization of thermal insulation thickness.

Paper	Economic method	Place	Opt. insulation thickness	Insulation material	Fuel
Ucar and Balo [40]	P_1–P_2	Turkey (Kocaeli, Aydin, Elazig, Agri)	They vary between 0.0106 and 0.0764 m depending on cities, and fuel types	Foamboard 3500, foamboard 1500, extr. polystyrene, fiberglass	Natural gas, Coal, Fuel-oil, Electricity, LPG
Ucar and Balo [23]	P_1–P_2	Turkey (Mersin, Sanliurfa, Elazig, Bitlis)	They vary in a wide range depending on *HDDs*, *CDDs*, insulation materials and fuel types	Extruded polystyrene, expanded polystyrene, nil siding, rock wool	Natural gas, Coal, Fuel-oil, Electricity, LPG
Yu et al. [16]	P_1–P_2	China (Shanghai, Changsha, Shaoguan, Chengdu)	0.053–0.236 m	Exp. polys., extr. polys., foamed polyurethane, perlite, foamed polyvinyl chloride	Electricity
Al-Khawaja [15]	–	Qatar	0.03 m (for wallmate)	Wallmate, fiberglass, polyethylene foam	Electricity
Sisman et al. [22]	*LCC*	Turkey (Izmir, Bursa, Eskisehir, Erzurum)	0.033 m, 0.047 m, 0.061 m, 0.080 m (for walls)	Rock wool	Coal
Farhanieh and Sattari [4]		Tehran/Iran	-	k = 0.03 W/mK (material is not specified)	–
Mahlia et al. [52]	P_1–P_2	Malaysia	They vary between about 0.04 and 0.10 m depending on insulation materials	Fiberglass–urethane, fiberglass (rigid), urethane (rigid), perlite, extruded polystyrene, urethane (roof deck)	Electricity
Kaynakli [38]	–	Bursa/Turkey	They vary between 0.053 and 0.124 m depending on fuel types	Polystyrene (for external walls), fiberglass (for ceiling), rock wool (for basement)	Natural gas, Coal, Fuel-oil, Electricity, LPG
Bolatturk [9]	*LCC*	Four cities for each *DD* region in Turkey (totally 16 cities)	They vary in a wide range (from 0.019 to 0.172 m) depending on cities and used fuel types for heating	Polystyrene	Natural gas, Coal, Fuel-oil, Electricity, LPG
Bolatturk [17]	P_1–P_2	Turkey (Adana, Antalya, Aydin, Hatay, Iskenderun, Izmir, Mersin)	They vary between 0.032 and 0.038 m for *CDHs* and between 0.016 and 0.027 m for *HDHs*.	Extruded polystyrene board	Natural gas for heating, Electricity for cooling
Comakli and Yuksel [41]	*LCC*	Turkey (Erzurum, Kars, Erzincan)	0.105 m, 0.107 m, 0.085 m	Styrofoam	Coal
Daouas et al. [26]	*LCC*	Tunisia	0.057 m	Expanded polystyrene, rock wool	Electricity
Dombayci et al. [33]	*LCC*	Denizli/Turkey	0.032-0.138 m depending on fuel types (for rock wool) 0.076-0.259 m depending on fuel types (for EPS)	Expanded polystyrene, rock wool	Natural gas, Coal, Fuel-oil, Electricity, LPG

studies found that natural gas and coal were more convenient heating fuels than other fuels (such as fuel-oil, electricity and LPG). Durmayaz et al. [19] and Durmayaz and Kadioglu [20] calculated the heating energy requirement and natural gas consumption in the biggest city centres of Turkey (Istanbul, Ankara, Bursa, Adana, Konya) using the degree-hours, but the optimum insulation thicknesses were not mentioned in their studies. Comakli and Yuksel [41] determined the optimum insulation thicknesses for Erzurum, Kars and Erzincan in cold regions of Turkey to be 0.104, 0.107 and 0.085 m, respectively, when coal was used for heating. Sisman et al. [22] investigated the optimum insulation thicknesses for external walls and roofs (ceilings) with respect to the different *HDD* regions. Four cities were considered in this study, and coal and rock wool were selected as the fuel and insulation material, respectively. Yu et al. [16] calculated the optimum thicknesses of five insulation materials (expanded polystyrene, extruded polystyrene, foamed polyurethane, perlite and foamed polyvinyl chloride) based on *HDDs* and *CDDs* for a typical residential wall in China. In that study, different wall orientations and surface colors were considered. It was concluded that the optimum insulation thicknesses

varied widely, and expanded polystyrene was the most economical insulation material because it had the highest life-cycle savings and the lowest payback period. Another study that considered external wall orientations was by Al-Khawaja [15]. The total costs among three different insulation materials (wallmate, fiberglass, and polyethylene foam) for light-colored and deep-colored surfaces were compared for Qatar, and sol-air temperature instead of air temperature was used in the analysis. By considering the climate of Tehran, Iran, Farhanieh and Sattari [4] investigated the variations of heat flux from/to external walls as a function of the insulation thickness for the spring, summer, fall, and winter seasons. It was emphasized that a substantial amount of energy savings could be achieved with insulation in external walls, but the optimum values for insulation were not given in that study. It was found that using a 0.025 m thick insulation for the external wall would save approximately 45% of the energy consumption in winter in Tehran. The studies related to the optimization of thermal insulation thickness and their results are summarized in Table 3.

The effects of insulation on the energy requirements for space-cooling were investigated by Bojic et al. [42], Bojic et al. [43], Cheung et al. [44], Al-Turki and Zaki [45] and Aktacir et al. [46]. Bojic et al. [43] investigated the influence of varying the location of the insulation layer within the outside walls on the yearly cooling load for two typical high-rise residential flats in Hong Kong. They found that the highest decrease in the yearly cooling load of up to 6.8% was obtained when a 0.05 m thick insulation layer was placed on the inside of envelope walls. However, the magnitude of the reductions depended on the investigated flats. Cheung et al. [44] focused on the annual required cooling load and the peak cooling load in the high-rise buildings. The effects of building envelope design parameters such as insulation (thickness and position), color of external walls, glazing systems, shading coefficient and glazing area, on these loads were examined. They showed that a saving of 31.4% in annual required cooling energy and 36.8% in peak cooling load could be achieved. Similarly, Ansari et al. [14] presented a simple model to investigate the effects of building parameters (orientation, window glass shade, number of glass panes, insulation, roof and floor types) on the building cooling load. In the study of Aktacir et al. [46], three different types of insulated buildings located in a hot region in Turkey, Adana, were considered, and the initial and the operating costs of air conditioning systems (constant-air-volume, CAV and variable-air-volume, VAV) were investigated. As a conclusion, the initial costs of CAV and VAV systems were reduced by 22%, and the operating costs of VAV and CAV systems were reduced by 25% and 33%, respectively, with respect to the no insulated building. Before this study, *LCC* analyses had been carried out by Aktacir et al. [53] for both air conditioning systems. Using the *LCC* analysis, the effect of insulated roof slabs on the energy needed for air conditioning was investigated by Halwatura and Jayasinghe [54] for Sri Lanka. Yoon et al. [55] studied crop storage insulation systems in Korea because there are no specific standards or guidelines for reduction of energy use in refrigerated structures. To determine the optimal configuration for the storage building insulation system, *LCC* analysis was used in that study. Soylemez and Unsal [56] studied on optimization of insulation thickness for refrigeration applications as well. Among the optimization studies, Asan [57] stated the importance of time lag and decrement factors in determination of optimum insulation position, and as a result, he found that the optimum position of insulation from the maximum time lag point of view was not practical (where two pieces of insulation are placed in a certain distance apart from each other in the wall). Placing half of the insulation in the mid-centre plane of the wall and the half of it in the outer surface of the wall gave very high time lags and low decrement factors (close to optimum values). Jaber [58] emphasized that the space heating in Jordan accounted for about 61% of residential energy consumption, and Kerosene and LPG were the popular domestic fuels used for heating. He investigated the variation of average heating demand (with and without wall insulation such as cavity, rock wool and polystyrene) for winter months.

Sodha et al. [59], Ozel and Pihtili [60,61], and Al-Sallal [62] investigated the most suitable location to apply insulation for the roof and/or walls. A numerical model was applied for 12 different roof and wall configurations during typical winter and summer days. The studies showed that the pieces of insulation had to be equal in thickness and placed at the outdoor surface of the roof/wall, in the middle of the roof/wall, and at the indoor surface of the roof/wall [60,61]. Al-Sallal [62] compared two types of roof insulation (polystyrene and fiberglass) in warm and cold climates (i.e., Texas and Minnesota) and found that the payback period in cold climates was shorter than that in warm climates.

One of the more recent studies on optimization based on *LCC* analysis was by Arici and Karabay [63], who investigated the optimum thickness of double-glazed windows for four cities (Iskenderun, Kocaeli, Ankara and Ardahan) located in different climatic zones in Turkey. They found that the optimum air layer thickness varied between approximately 12 and 15 mm depending on the climate zone and fuel type (natural gas, coal, fuel-oil, electricity or LPG), and up to 60% energy saving could be achieved by a well-optimized double-glazed window. Similarly, Aydin [64] focused on the determining the optimum thickness of the air layer for the double-paned windows for four different cities (Antalya, Ankara, Trabzon and Kars) that characterized the different climates in Turkey. Based on the simulation results, the range of the optimum thickness was found to be 18–21 mm for Antalya, 15–18 mm for Ankara and Trabzon, and 12–15 mm for Kars. Moreover, it was emphasized that if the optimum values were used, the following energy reductions could be obtained: 40% for Antalya, 34% for Trabzon, 29% for Ankara, and 21% for Kars.

Several studies used the sol–air temperature instead of the outdoor ambient air temperature to study the optimum insulation thickness by calculating the heating and cooling *DD*s [15–17,60,65]. The sol–air temperature is a concept related to the outside air temperature and the solar radiative flux, and the temperature considers the incident solar radiation on a wall. The effect of solar radiation is accounted for by considering the outside temperature to be higher by an amount equivalent to the effect of solar radiation. The sol–air temperature is given by [15,17,66]

$$T_{\text{sol-air}} = T_o + \frac{\alpha_s \dot{q}_s}{h_o} - \frac{\varepsilon\sigma(T_o^4 - T_{surr}^4)}{h_o} \tag{3}$$

where T_o is the outside air temperature, α_s the solar absorptivity of the surface, h_o is the outer surface combined convection and radiation heat transfer coefficient, $\dot{q}_s$ is the solar radiation incident on the surface, ε is the emissivity of the surface, σ is the Stefan-Boltzmann constant, and T_{surr} is sky and surrounding surface temperature. Hence, the annual heating and cooling degree-days can be expressed as follows:

$$HDD = \sum_{1}^{365} (T_b - T_{\text{sol-air}})^+ \tag{4}$$

$$CDD = \sum_{1}^{365} (T_{\text{sol-air}} - T_b)^+ \tag{5}$$

Studies on the effect of an electricity tariff on optimum insulation thickness were carried out by Al-Sanea et al. [39] and Gustafsson and Karlson [67]. Al-Sanea et al. [39] used a dynamic heat-transfer model based on a finite-volume and an economic model based on a life-cycle cost (LCC) analysis. They investigated the optimum insulation thicknesses for the climate conditions in

Riyadh, Saudi Arabia using expanded polystyrene as the insulation material. An experimental study was carried out by Cabeza et al. [68] to evaluate the influence of the most common insulation materials used in buildings in Spain, such as polyurethane, polystyrene and mineral wool. For this purpose, four house-like cubicles were constructed (with a size of 2.4 m × 2.4 m × 2.4 m). They found that by applying a layer of 0.05 m thick insulation, the electrical energy consumption for air conditioners decreased up to 64% in summer and up to 37% for electric oil radiators in winter. Furthermore, it was emphasized in the study that the lowest energy consumption was obtained when polyurethane was used as insulation, followed by mineral wool (5% higher) and the polystyrene (9% higher).

Kossecka and Kosny [37] focused on the effect of insulation location and the associated energy performance for residential buildings with six characteristics wall configurations for six different US climates (Atlanta, Denver, Miami, Minneapolis, Phoenix and Washington, DC). They emphasized that material configuration of the exterior wall could significantly affect the annual thermal performance of the whole building, but this effect depended on the type of climate. The best thermal performance was obtained when massive material layers were located at the inner side of the walls. Differences in total energy demand between the configuration "all insulation inside" and the most effective configuration (from the point of view of energy savings) "all insulation outside" may exceed 11% for a continuously used residential building.

Several investigations have focused on optimizing the building shape to minimize energy use and cost [69–71]. Ourghi et al. [71] presented a simplified analysis method to predict the impact of the shape of an office building on its annual cooling energy and total energy use. In the analysis, they considered the parameters such as building geometry, glazing type, glazing area and climate. These studies emphasized the strong correlation between the shape of a building and its energy consumption.

3.2. Studies considering dynamic thermal conditions

A small number of studies applied the dynamic time-dependent model instead of the degree-time method to compute the heat transfer in a composite wall. The accurate determination of the heat gain/loss through the walls or roofs of a building is very important in selecting a suitable heating or cooling systems that can efficiently utilize energy, and in computing the amount of thermal insulation required in walls. Kaska et al. [72] and Kaska and Yumrutas [73] investigated, experimentally and theoretically, the total equivalent temperature difference (TETD) values for multilayer walls and flat roofs; these values could be used to calculate the cooling load of a building. To compute yearly heat transmission loads under steady periodic conditions, Al-Sanea and Zedan [74,75] and Al-Sanea et al. [39] used a dynamic model based on an implicit finite-volume procedure, whereas Ozel [5] used the implicit finite-difference method. Kumar et al. [76] presented a techno-economic model based on time-dependent for evaluating optimum distribution of insulation over various components of an air-conditioned building in Indian cities (New Delhi, Srinagar, Madras and Jodhpur). The results showed that the insulation over the roof provided the most savings whereas on the south oriented wall least. Then, the same methodology was also used by Deshmukh et al. [77].

An analytical method based on the Complex Finite Fourier Transform (CFFT) technique was used in the studies of Daouas et al. [26], Daouas [78], Yumrutas et al. [79], and Yumrutas et al. [80]. Two typical wall structures (brick/brick and stone/brick sandwich walls) and two types of insulation materials (expanded polystyrene and rock wool) were analyzed by Daouas et al. [26] to determine the most economical combination of structure and material selection. Expanded polystyrene was found to be the most profitable insulation material for Tunisia. Moreover, the study concluded that the combination of expanded polystyrene and the stone/brick sandwich wall structure had energy savings of 58% with a payback period of 3.11 years with an optimum insulation thickness of 0.057 m. In a more recent study by Daouas [78], the optimum insulation thickness was found to be 0.101 m, which led to energy savings of 71.33% with a payback period of 3.29 years for the southern orientation. Furthermore, it was noted that wall orientation had a small effect on the optimum insulation thickness, but a more significant effect on energy savings. Yumrutas et al. [79], Yumrutas et al. [80] proposed an analytical solution for the problem of heat transfer through multilayer walls and flat roofs, but, any optimization procedure on insulation thickness was not given in their studies. Djuric et al. [81] optimized the total cost including energy, insulation and the radiator costs, on the basis of the thermal comfort by using dynamic thermal simulation software (*EnergyPlus*) and generic optimization program (*GenOpt*). In that study, the thermal comfort was represented by Predicted Percentage of Dissatisfied (PPD) index. Another interesting study conducted by Masoso and Grobler [82] used the same thermal simulation software (*EnergyPlus*) for office buildings in the hot and dry climate of Botswana, and found that adding wall insulation did not always reduce the annual energy consumption. They hypothesized that adding wall insulation could increase the annual energy consumption because of internal heat gains. In that study, the cooling set-point temperature was gradually increased, and the annual cooling energy savings changed from positive to negative after a specific temperature (approx. 26 °C) for 0.08 m of extruded polystyrene. This temperature was named the "*point of thermal inflexion*" by the authors. Radhi [83] focused on the energy consumption of air-conditioned commercial buildings in Bahrain, and used a building simulation program (Visual DOE) to model the cooling load and the electric energy consumed. Simulation results showed that if the building envelope was well-insulated and efficient glazing was used, the energy use and CO_2 emissions could be reduced by 25% and 7.1%, respectively. A parametric study [84] was conducted with the building simulation program (Visual DOE) to investigate the impact on efficiency measures of energy use in office buildings located Dammam, Saudi Arabia. The study showed, respectively, 2%, 6% and 7% reductions in the total electricity consumption as the wall and roof insulation increased from 0.05 m to 0.075 m, and as energy-efficient lamps and low-e double-glazed window were used instead of the existing glazing system.

4. Thermal insulation materials

Some researchers focused on thermal insulation materials and their properties [85–87,13,88–91]. Papadopoulus and Giama [85] evaluated the production process of two insulation materials (stone wool and extruded polystyrene) based on environmental criteria with *LCC* analysis. The effects of insulation on energy and environment were also examined in Lollini et al. [87]. Al-Homoud [13] remarked on the importance of properly using thermal insulation in buildings to reduce the annual energy consumption and the required air conditioning system size. He then presented an overview of the basic principles of thermal insulation and surveyed the most commonly used building insulation materials while taking note of their performance characteristics and proper applications. The thermal properties of new composite insulation materials were experimentally tested with thermal conductivity tests using the heat flux method in Choi et al. [88]. Mahlia et al. [52] presented a polynomial function representing the relationship between thermal conductivity and the optimum thickness of the insulation material. In that study, different insulation materials (fiberglass–urethane, fiberglass-rigid, urethane-rigid, perlite, extruded polystyrene, and urethane-roof

deck) were considered; the thermal conductivities of these insulation materials varied widely from 0.02 to 0.055 W/mK. Anastaselos et al. [89] presented an assessment tool for thermal insulation solutions in terms of energy, economic and environmental evaluation. The assessment tool was applied to a double cavity wall and external insulation composite system. It was concluded that the implementation of an external insulation composite system was preferable.

The performance of the insulation materials is mainly determined by its thermal conductivity, which is dependent on the density, porosity, moisture content, and mean temperature difference of the material. Thermal insulation materials in buildings are exposed to significant and continuous temperature variations due to varying outdoor air temperature and solar radiation. Therefore, the thermal conductivity of the insulation material can vary due to changes in both moisture content and temperature. The relationship between the temperature and the thermal conductivity of various insulation materials (fiberglass, wood wool, mineral wool, rock wool, polyethylene, polyurethane, and polystyrene) was investigated by Budaiwi et al. [90] and Abdou and Budaiwi [91]. They concluded that thermal conductivity varied with operating temperature for all tested materials and that a larger temperature gradient resulted in higher thermal conductivity. Polyurethane and polystyrene had the lowest rate of change in thermal conductivity while polyethylene and wood wool had much greater rates of change.

5. Different approaches and applications of thermal insulation systems

Vapor condensation in walls is one of the problems related to buildings [92]. The optimization method used in Arslan and Kose [92] and Ucar [93] considered the condensed vapor in buildings. In these studies, exergo-economic calculations, which depend on minimizing the total cost equation, were conducted using the equation given by

$$C_t = C_F + Z^{Cl} + Z^{OM} \tag{6}$$

where C_t is the total cost, C_{F} is the fuel cost, and $Z^{C\ l}$ and Z^{OM} are the investment cost and the operation and maintenance costs, respectively. Z^{OM} was taken to be zero because there is no cost of operation and maintenance [92,93]. $Z^{C\ l}$ and C_{F} are given by

$$Z^{\mathrm{Cl}} = C_{\mathrm{ins}} x_{\mathrm{ins}} \tag{7}$$

$$C_F = c_F \frac{Ex_{\mathrm{loss},\ Q} + Ex_d}{Ex_F - Ex_{\mathrm{loss},\ S}} \tag{8}$$

where $Ex_{\mathrm{loss,Q}}$ is the exergy loss due to heat transfer, Ex_{d} is the exergy destruction due to condensed vapor, Ex_{F} is the exergy of fuel, $Ex_{\mathrm{loss,S}}$ is the exergy loss due to stack gases, C_{ins} is the insulation cost.To determine the $Ex_{\mathrm{loss,S}}$, the first and second laws of thermodynamics were applied, respectively, to a complete combustion process. The other exergy equations are given by

$$Ex_{\mathrm{loss},\ Q} = \frac{86.4DD}{(R_w + x_{\mathrm{ins}}/k_{\mathrm{ins}})\eta} \tag{9}$$

$$Ex_{\mathrm{d}} = m_c\,[(h_i - h_o) - T_0(s_i - s_o)] \tag{10}$$

$$Ex_F = \left(1 - \frac{T_{rt}}{T_{cc}}\right) Q_F \tag{11}$$

The details of the equations could be found in Arslan and Kose [92] and Ucar [93]. By using these equations, Arslan and Kose [92] studied one city in Turkey (Kutahya) located in the third *DD* region, and the extruded polystyrene foam and lignite were used as the insulation and fuel, respectively. The optimum insulation thicknesses were found to be 0.058 m, 0.066 m, and 0.073 m for indoor temperatures of 18, 20 and 22 °C, respectively. Recently, a similar approach was applied by Ucar [93] in which the optimum insulation thicknesses were obtained considering condensed vapor in external walls for four cities in Turkey, namely Antalya, Istanbul, Elazig, and Erzurum. The cities are separately located in four different *DD* regions. The optimum insulation thickness varied from 0.031 to 0.082 m depending on cities and indoor temperatures of 18, 20, and 22 °C. As an example, for the indoor temperatures of 20 °C, the optimum insulation thicknesses were obtained as 0.038 m, 0.046 m, 0.057 m, and 0.074 m for Antalya, Istanbul, Elazig, and Erzurum, respectively.

Studies on thermal insulation for the cylindrical geometry are relatively fewer than that for buildings. The economic insulation thickness for a pipe depends on a large number of parameters, such as pipe sizes, cost, conductivity, temperature difference and annual operation hours [94,95]. Kalyon and Sahin [96] studied the optimum insulation thickness of a pipe subjected to convective heat transfer that minimized the heat loss. Sahin [97] optimized the variation of thermal insulation thickness of a tube for space applications numerically to minimize the radiative heat loss to the ambient. Li and Chow [98] studied on the optimum insulation thickness for tubes of different sizes. Methods for protecting water pipes, in cold regions against freezing, by thermal insulation material and heating cable were analyzed. In that study, *LCC* analysis was used for optimization of insulation thickness (fiberglass–urethane), and the variation of optimum insulation thickness with different outer tube diameters and outside air temperatures was calculated. As a conclusion, the optimum thickness increased with increasing the outer tube diameter and decreasing the outside air temperature, however, the environmental effect was not significant.

Review studies carried out by Kaushika and Sumathy [99] and Wong et al. [100] focused on transparent insulation materials and systems, which included transparent cellular arrays made of glass or polycarbonate materials with a honeycomb arrangement between the two bounding surfaces. It was emphasized that the transparent insulation materials were used extensively for flat-plate solar collectors prior to being used for building applications.

Castell et al. [101] experimentally investigated the incorporation of phase change materials in two typical brick constructions in real conditions to determine the energy savings achieved. Banfi et al. [102] experimentally evaluated the willingness of consumers to pay for energy saving-measures in residential buildings (both in renovated and new buildings) in Switzerland. The energy-saving measures that benefited individual consumers and the environment were the characteristics of the windows, the insulation of the facade, and the air ventilation system. In Bahadori and Vuthaluru [103], simple correlations were formulated to estimate the thickness of thermal insulation required to arrive at a desired heat flow or surface temperature for flat surfaces, ducts and pipes. The proposed correlation covered the temperature difference between ambient temperature and outside temperature up to 250 °C and the temperature drop through insulation up to 1000 °C. The proposed correlation calculated the thermal thickness for flat surfaces up to 200 mm and predicted the thermal thickness for ducts and pipes with outside diameters up to 2400 mm. Another study reported by the same authors (Bahadori and Vuthaluru [104]) focused on only optimum thickness of thermal insulation as a function of steel pipe. The correlation proposed in that study depended on pipe diameter, thermal conductivity of insulation material for surface temperatures at 100, 300, 500 and 700 °C. As a conclusion, they reached that the optimum insulation thickness increased by diminishing increments with increasing outside diameter of steel pipe.

Lorente and Bejan [105] addressed the problem of optimizing the internal structure of a vertical composite wall that can meet

the requirements of maximizing the thermal insulation with a fixed mechanical strength. The effect of block cavities on heat transfer was examined by Antar [106] to achieve more energy savings for the end users. He emphasized that changing the layout of the cavities could substantially decrease the heat leak and provide better thermal insulation without affecting the structural characteristics of the blocks. In the literature, several studies partitioned the cavities in the block to reduce the heat transfer rate [107–109]. The insulations used in the study by Habali et al. [110], rock wool and polyurethane, were used to insulate a long-term concrete storage tank. In the study, the effect of the insulation thickness on the total cost of a solar system used in space heating and domestic hot water systems was investigated.

6. Financial analysis methods

In the literature, several financial methods were used to optimize the thermal insulation thickness of external walls. One of the financial analysis methods was the Simple Payback Period. This method is based on the time required to repay the initial capital investment with the operating savings attributed to that investment. The main drawback of this simple analysis is that it does not take into account the time value of money, a very important financial consideration [111]. The more commonly used method is the Life Cycle Cost (*LCC*) analysis [26,33,41,112,113]. This analysis calculates the cost of a system or component over its entire lifetime. The amount of net energy savings via insulation over a lifetime (*LT*) is evaluated in the present value using the present worth factor (*PWF*). The *PWF*, which depends upon the inflation rate (i), and the discount rate (d), is calculated as [2,114,115]

$$PWF = \left(\frac{1+i}{d-i}\right)\left[1-\left(\frac{1+i}{1+d}\right)^{LT}\right] \quad (if\ d \neq i) \tag{12}$$

$$PWF = \frac{LT}{1+d} \quad (if\ d \neq i) \tag{13}$$

LT could be assumed to be 10 years [22,23,33,41], 20 years [16,29,52,56], 25 years [15] or 30 years [26,78,87]. After calculating the *PWF* value, the total cost based on the number of heating and cooling degree-days can be expressed as follows

$$C_{t,H} = C_{\text{ins}}x + \frac{86400 HDD C_f PWF}{(R_{t,w}+x/k)Hu\eta} \tag{14}$$

$$C_{t,C} = C_{ins}x + \frac{86400 CDD C_e PWF}{(R_{t,w}+x/k)COP} \tag{15}$$

where C_{ins} is the cost of insulation material per unit volume, Hu is lower heating value of the fuel, η is efficiency of the heating system, C_f is the cost of fuel, $R_{t,w}$ is the total wall thermal resistance excluding the insulation layer, x and k are the thickness and thermal conductivity of insulation material, respectively, The optimum insulation thickness for annual (heating and cooling) energy requirements is obtained by minimizing the sum of eqs. (14) and (15). The derivative of the total cost equation with respect to insulation thickness is taken and set equal to zero, then the optimum insulation thickness (x_{opt}) is obtained as

$$x_{opt} = \left(\frac{86400 PWF(C_f HDD/\eta\ Hu + C_e CDD/COP)k}{C_{ins}}\right)^{1/2} - R_{t,w}k \tag{16}$$

where C_e is the cost of electricity since the cooling system is supplied with electricity and *COP* is the coefficient of performance of the cooling system, which depends on the operating parameters; on average, it is assumed to be 2.5 [17,56].

After determining the optimum insulation thickness most studies compute the payback period of the insulation cost. The payback period is the amount of time (typically measured in years) to recover the initial investment in an opportunity. This value represents the discounted payback period of the specific thickness compared to the reference thickness. The reference thickness is set as zero in order for the payback period to be compared to the un-insulated condition.

6.1. The P_1–P_2 method

Several studies used the P_1–P_2 method to calculate the net energy savings [16,17,40,52,56,116]. P_1 is the life cycle energy related to the market discount rate d (for the value of money), the inflation rate i (for the energy cost), and the economic analysis period (*or* the technical lifetime of the applied insulation in years [56], *LT*). The value of P_1 can be calculated for residential applications by [52,117]

$$P_1 = \sum_{j=1}^{LT} \frac{(1+i)^{j-1}}{(1+d)^j} = \left| \begin{array}{ll} \dfrac{1}{(d-i)}\left[1-\left(\dfrac{1+i}{1+d}\right)^{LT}\right] & i \neq d \\ \dfrac{LT}{1+i} & i = d \end{array} \right. \tag{17}$$

P_2 is the ratio of the life cycle expenditures incurred because of the additional capital investment to the initial investment, which can be calculated by

$$P_2 = D + (1-D)P_1 + M_s P_1 - \frac{R_v}{(1+d)^{LT}} \tag{18}$$

where D is the ratio of the down payment to the initial investment, M_s is the ratio of first year miscellaneous costs (maintenance, insurance, and other incidental costs) to initial investment, and R_v is the ratio of the resale value at the end of the economic period to the initial investment. If no additional capital is invested other than the initial investment (such as maintenance and operation costs), P_2 can be taken as 1 [52,56].

7. An application for determining the optimum thickness

A practical application for optimizing the insulation thickness based on degree-days was conducted by using the *LCC* analysis in the present work. Iskenderun, located in the first *DD* region in Turkey, was chosen as an example. The weather data used in energy analysis determined the accuracy and characteristics of the results. Therefore, the database used in energy requirement calculations should cover a long period and depend on recent values [21]. In this study, approximately 20 year-ambient temperature (dry bulb) data were used to determine the heating and cooling degree-days. The data were taken from The State Meteorological Affairs General Directorate [118]. Using these values, the variation of heating and cooling *DD*s is plotted in Fig. 2. The *HDD*s and *CDD*s values for Iskenderun were computed as 674 and 448, respectively.

By using the *HDD*s and *CDD*s, the annual heating and cooling transmission loads could be estimated. The variation of these loads and the decreasing ratio of the total annual transmission load with the insulation thickness are shown in Figs. 3 and 4. The particular parameters used in the calculations are given in Table 4. As the insulation thickness increased, both the heating and cooling loads per square meter of wall decreased, as expected. The annual total transmission load dropped to 50% with an insulation thickness of only 0.02 m, and it dropped under 20% with an insulation thickness of 0.10 m, as seen in Fig. 4.

In the calculations, the cooling system was supplied with electricity, and natural gas was chosen as the heating fuel because it is widely used for space heating in Turkey. The costs of electricity and natural gas are also given in Table 4. The variation of cost curves (total heating-cooling energy and insulation) with insulation thickness and the optimum economic thickness of the insulation can be seen in Fig. 5. The optimum insulation thickness minimizing the

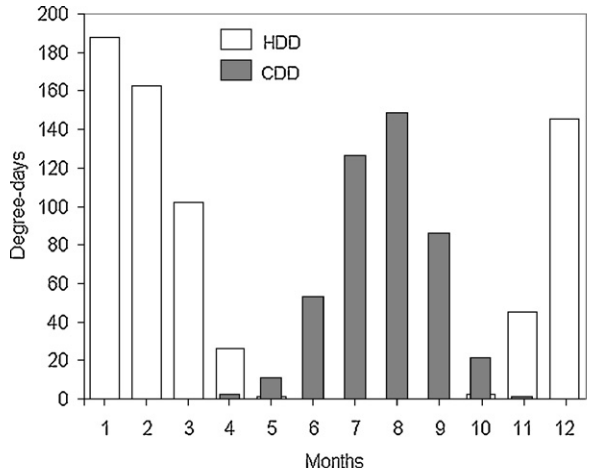

Fig. 2. The variation of *HDD*s and *CDD*s during year.

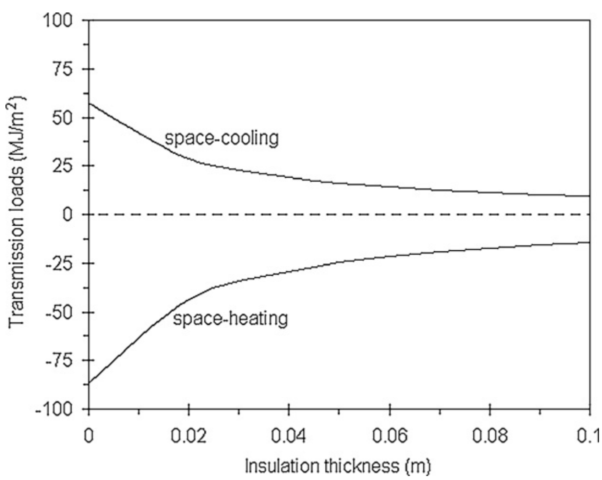

Fig. 3. The variation of annual heating and cooling transmission loads with insulation thickness.

life cycle cost over a lifetime of 10 years was 0.023 m. The effect of *DD* values on the optimum insulation thickness is seen in Fig. 6. The optimum insulation thickness did not vary linearly with the *DD* values; it increased by diminishing increments with increasing

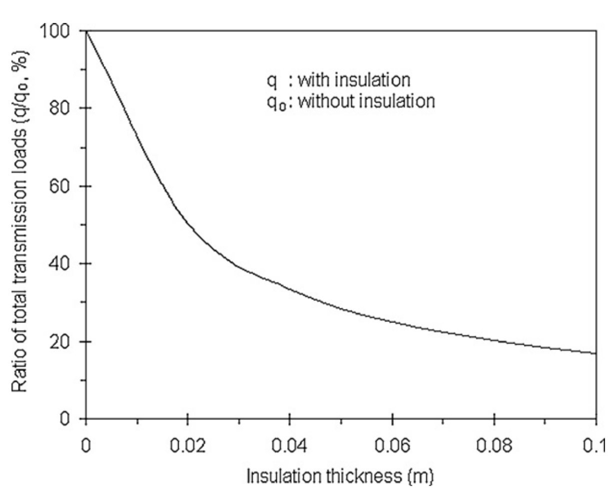

Fig. 4. The variation of the decreasing ratio of total annual transmission load with insulation thickness.

Table 4
The parameters used in the calculations.

Parameter	Value
Overall heat transfer coefficient of wall	$U = 1/(R_{ins} + 0.672)$ W/m^{2}K [17]
Insulation (polystyrene)	
Density	$\rho > 30$ kg/m^3
Conductivity	$k = 0.030$ W/mK [9,26,92]
Material cost	$C_{ins} = 170$ USD/m^3
Natural gas (in heating)	
Price, C_f	0.367 USD/m^3
Lower heating value, Hu	34.526×10^6 J/m^3 [17]
Efficiency of heating system, η	0.93 [17,33]
Electricity (in cooling)	
Price, C_e	0.118 USD/kWh
COP	2.5 [56]
Financial parameters	
Inflation rate, i	5%
Discount rate, d	7%
Lifetime, LT	10 [22,23,33,41]
Present worth factor, PWF	9.03

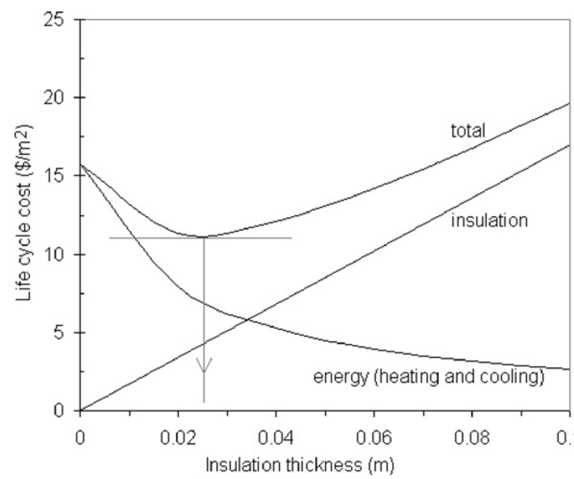

Fig. 5. The variation of total life cycle cost and insulation cost with insulation thickness.

*DD*s. On the other hand, optimum values for *CDD*s were higher than those for *HDD*s because of the unit cost of energy.

The *HDD*s and *CDD*s in Turkey were 690 and 398 for Iskenderun and 5137 and 0 for Ardahan, respectively [21]. By using these values, the annual total (heating and cooling) energy requirements were calculated to vary between approximately 140

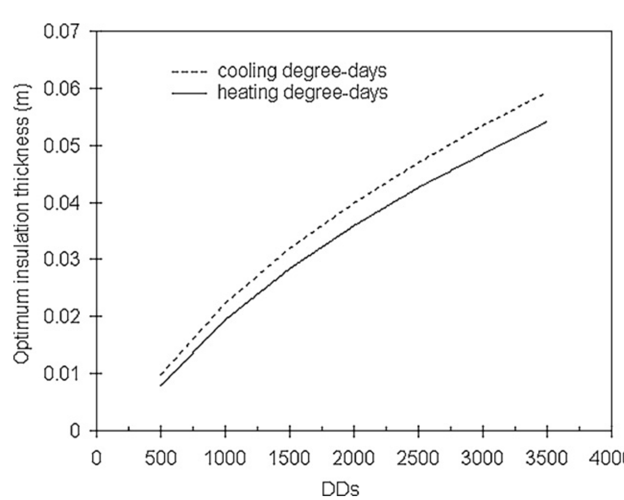

Fig. 6. The variation of optimum insulation thickness with degree-days.

and 660 MJ/m^2, while the optimum insulation thicknesses varied between 0.022 and 0.070 m. This meant that a building in Ardahan required 4.7 times more annual energy and 3.1 times thicker insulation than a building in Iskenderun.

8. Conclusions

In the last decade, a significant increase in the number of studies on building design parameters, building envelope characteristics and thermal insulation applications has been observed, which aim to reduce the annual energy consumption required to heat and/or cool buildings. Reducing the energy consumption in buildings is important because of limited energy resources and environmental concerns. This study presented a literature review on the thermal insulation applications to external walls for buildings, and focused especially on the determination of an economic insulation thickness. The insulation materials and fuel types encountered in the literature were compiled and presented. The effects of insulation and other building design parameters on energy consumption in buildings and on environmental emissions were investigated. This study could be a useful resource for researchers because since it includes a review of thermal insulation systems (for both the building envelope and other applications), the procedure of optimization and a practical application example.

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